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Annual Report for NAG 5-2556

Five separate *ASCA* observing programs are now housed under this grant number; in addition, the PI's work on other datasets on which he is a coI has received modest support from this grant. We have now obtained the data from all five PI programs, although in one case problems with the observation require reprocessing (or, perhaps, reobservation). We have completed the analysis for three of the programs and papers are in draft form. In another case, the analysis is virtually complete, although the interpretation is proving problematic, while, as noted above, the fourth dataset contains some unresolved problems. In this annual report, we provide a brief update of the status of each project.

I. Through the Gas Darkly: An Unobscured Image of the Milky Way

This program was a pilot study to determine whether or not a mosaic of a very large number of very short *ASCA* observations along the plane of the Milky Way would prove useful in providing low-luminosity source counts and a spatially resolved image of the mysterious diffuse Galactic Ridge emission. We obtained 14 pointings (~ 2500 s each) in a region between Galactic longitude 22 and 24.5, and within ± 0.5 degrees of the plane. Only two faint discrete sources were detected. The Ridge emission was evident in all pointings, with strong Si, S, and Fe lines prominent in the "background" spectra. It appeared that the plasma properties differed on a one-degree scale, but the statistics of these short exposures made it difficult to draw quantitative conclusions. It was decided that fewer, longer pointings would probably be most useful in a Galactic Plane survey, and that such a GIS program would best be carried out after the productive life of the SIS instruments come to an end.

Nonetheless, these data turned out to be crucial in the analysis of one of the pointed PV phase observations conducted by the PI. In Blanton and Helfand (1996 ApJ, Oct 20, in press), we present the results on the luminous composite supernova Remnant G29.7-0.3 which rely on the background spectrum obtained as part of the Plane Survey program. The combined spectrum is published along with a cautionary note to other observers who might otherwise use standard *ASCA* background subtraction techniques in this complex region of background emission near the Galactic Plane.

II. New Starburst Galaxies with Extreme X-ray Luminosities

The spectacular southern galaxy NGC 3256, with a highly disturbed central region and bright, extended tidal tails, is an excellent example of a merging galaxy system. Due to its extreme brightness in the near infrared and strong narrow optical emission-line spectrum, NGC 3256 is considered to be a "super starburst" galaxy (Joseph & Wright 1985), in the midst of an especially vigorous episode of star formation. The starburst and merger events are expected, ultimately, to render NGC 3256 a gas-depleted elliptical galaxy (Graham et al. 1984).

NGC 3256 is seemingly a luminous X-ray source as well. The galaxy is among the *IRAS* Point Source Catalog sources detected in the *ROSAT* All-Sky Survey (RASS; Boller et al. 1992). Its soft (0.1–2.4 keV) X-ray luminosity L_{x} is listed at 2×10^{42}erg s^{-1}, which would make it the most luminous X-ray starburst galaxy known (see Fabbiano 1989). Our followup of 17 objects in the Boller et al. sample which have high X-ray luminosities but optical classifications as normal spiral galaxies or starbursts revealed that most are actually previously unrecognized Seyfert galaxies (Moran, Halpern, & Helfand 1994); NGC 3256, however, proved to be the one starburst galaxy in this group securely identified as an X-ray source.

X-ray–luminous starburst galaxies may represent a significant component of the cosmic X-ray background (XRB; Bookbinder et al. 1980; Stewart et al. 1982; Griffiths & Padovani 1990). To do so, they would have to have hard broad-band X-ray spectra to explain the shape of the XRB spectrum (Fabian & Barcons 1992) and an appropriate evolution to account for, along with other known sources of contribution, the observed intensity of the XRB (Lonsdale & Harmon 1991). Detailed investigation of the X-ray emission from starburst galaxies is important in this context, and NGC 3256, because of its apparently exceptional luminosity, offers a unique opportunity for such study. Furthermore, with an infrared luminosity of $\sim 6 \times 10^{11}$ $L_{\odot}$ (Sargent, Sanders, & Phillips 1989), NGC 3256 is an ' 'ultraluminous" infrared galaxy. Hard X-ray observations of NGC 3256 could also be used to search for a buried active nucleus and, thus, to comment on the proposition that ultraluminous infrared galaxies are linked to the origin of quasars (Sanders et al. 1988). In a paper now in draft form, we explore both of these issues with the use of X-ray images and spectra of NGC 3256 obtained with the *ROSAT* and *ASCA* observatories.

We observed NGC 3256 in the 0.6–10 keV range with the *ASCA* satellite (Tanaka, Inoue, & Holt 1994) on 1993 December 6. Total exposures of 33.2 and 32.4 ksec were obtained with *ASCA*'s Solid-state Imaging Spectrometers SIS0 and SIS1, respectively. An exposure of 36.1 ksec was achieved with each of the two Gas Imaging Spectrometers (GIS2 and GIS3) on board *ASCA*. Periods of high background were filtered from the photon event files for each instrument following the guidelines described in The ABC Guide to *ASCA* Data Reduction (Day et al. 1995). The SIS detectors were operated in 1-CCD mode. Source counts in the SIS images were collected within a $3'$ radius circular region centered on the galaxy. Background was measured in source-free areas on the chip approximately the same distance off-axis as the galaxy. In the GIS images, source counts were collected within a $6'$ radius region centered on NGC 3256. Background was measured in a region of equal area positioned at the same off-axis angle as the source, but on the opposite side of the optical axis. The background-subtracted spectra obtained with the SIS0, SIS1, GIS2, and GIS3 instruments contain 1116, 1039, 786, and 1000 counts, respectively, and were rebinned to provide a minimum of 25 (SIS) or 50 (GIS) counts per energy channel.

The *ROSAT* data we have collected on this source provide two important clues for the interpretation of the X-ray emission from NGC 3256: 1) the published high luminosity for this source is in error by nearly an order of magnitude and, in fact, it's luminosity is at the upper end of that for normal starburst galaxies, and 2) the bulk of the X-ray emission is extended. However, a comprehensive understanding of NGC 3256's X-ray properties is only possible through the analysis of its emission over a wide bandpass, which our *ASCA* observation in the 0.5–8 keV range provides. Although *ROSAT* is sensitive down to 0.1 keV, there is virtually no flux below 0.5 keV in the PSPC spectrum of NGC 3256 due to its limited number of counts and the high Galactic column density toward the galaxy;

thus, it contributes little additional information for our broad-band analysis. Similarly, the *ASCA* GIS2 spectrum contains far fewer counts than the spectra obtained with the other instruments on board *ASCA*, presumably because the source in this observation was more severely vignetted. Therefore, the spectral analysis presented here consists of simultaneous fits to the SIS0, SIS1, and GIS3 spectra of NGC 3256, all of which contain at least 1000 counts. We have fitted these spectra with a variety of models containing up to three spectral components. In each fit, we permitted normalizations of the components applied to the SIS and GIS spectra to be independent parameters to allow for absolute calibration differences between the two types of instruments.

The quality of the fit to the PSPC spectrum obtained with a Raymond-Smith model (R-S) and the extended nature of the soft X-ray emission, revealed in the HRI image, makes a R-S plasma an obvious model with which to fit the *ASCA* spectra of NGC 3256. Furthermore, strong emission lines are plainly visible in the SIS0 spectrum, confirming the presence of a hot, optically thin gas. But a single R-S component provides a very poor fit to the *ASCA* spectra ($\chi^2 = 222$ for 101 degrees of freedom), so we must consider more complex models.

Two-component models involving a soft R-S plasma and a harder thermal bremsstrahlung (TB) component provide excellent fits to the *ASCA* spectra. In all such fits, the values of χ^2_ν ($= \chi^2/\nu$, where ν is the number of degrees of freedom) obtained are less than unity. Consistent spectral parameters for the two components are derived for a variety of absorption scenarios (*i.e.*, the amount each component is absorbed is the same or different, and constrained to the Galactic $N_{\rm H}$ value or a free parameter). The *ASCA* spectra of NGC 3256 with the (TB + R-S) model are displayed in Figure 1. Note the systematic displacement of the fit residuals near the magnesium and silicon emission lines at ~ 1.4 and 1.8 keV in the upper panel of the figure. Two-component fits of comparable quality are obtained when a power law is substituted for the hard TB component. The values of the best-fit power-law photon index Γ range from 2.0 to 2.4, whereas the values of $N_{\rm H}$, the characteristic temperature kT of the R-S component, and χ^2 are virtually identical to those obtained in the various (TB + R-S) fits.

We are in the process of writing up these results which lead to an interpretation of the X-ray properties of this galaxy similar to that advanced by Moran and Lehnardt (1996) for the prototypical starburst M82. The paper will be submitted for publication in the Astrophysical Journal in the coming months.

III. The 2-50 keV Spectrum of the Quasar 1508+5714

Observations with the *Einstein* and *ROSAT* observatories have revealed that, over a broad range of fluxes, quasars are the most common extragalactic X-ray sources (Stocke et al. 1991; Boyle et al. 1993). But the predominance of low redshifts among X-ray–detected quasars and the limited spectral response of these instruments have focused most high-energy studies of quasars on their soft X-ray properties (*e.g.*, Ku, Helfand, & Lucy 1980; Zamorani et al. 1981; Avni & Tananbaum 1986; Wilkes & Elvis 1987; Laor et al. 1994; Wilkes et al. 1994). Detailed investigation of their *hard* X-ray spectra has, until recently, only been possible for relatively few nearby and exceptionally bright objects (Lawson et al.

Figure 1: The two-component fit to the *ASCA* NGC 3256 spectrum including a Raymond-Smith thermal plasma responsible for the prominent line emission and a thermal bremsstrahlung component to explain the harder tail.

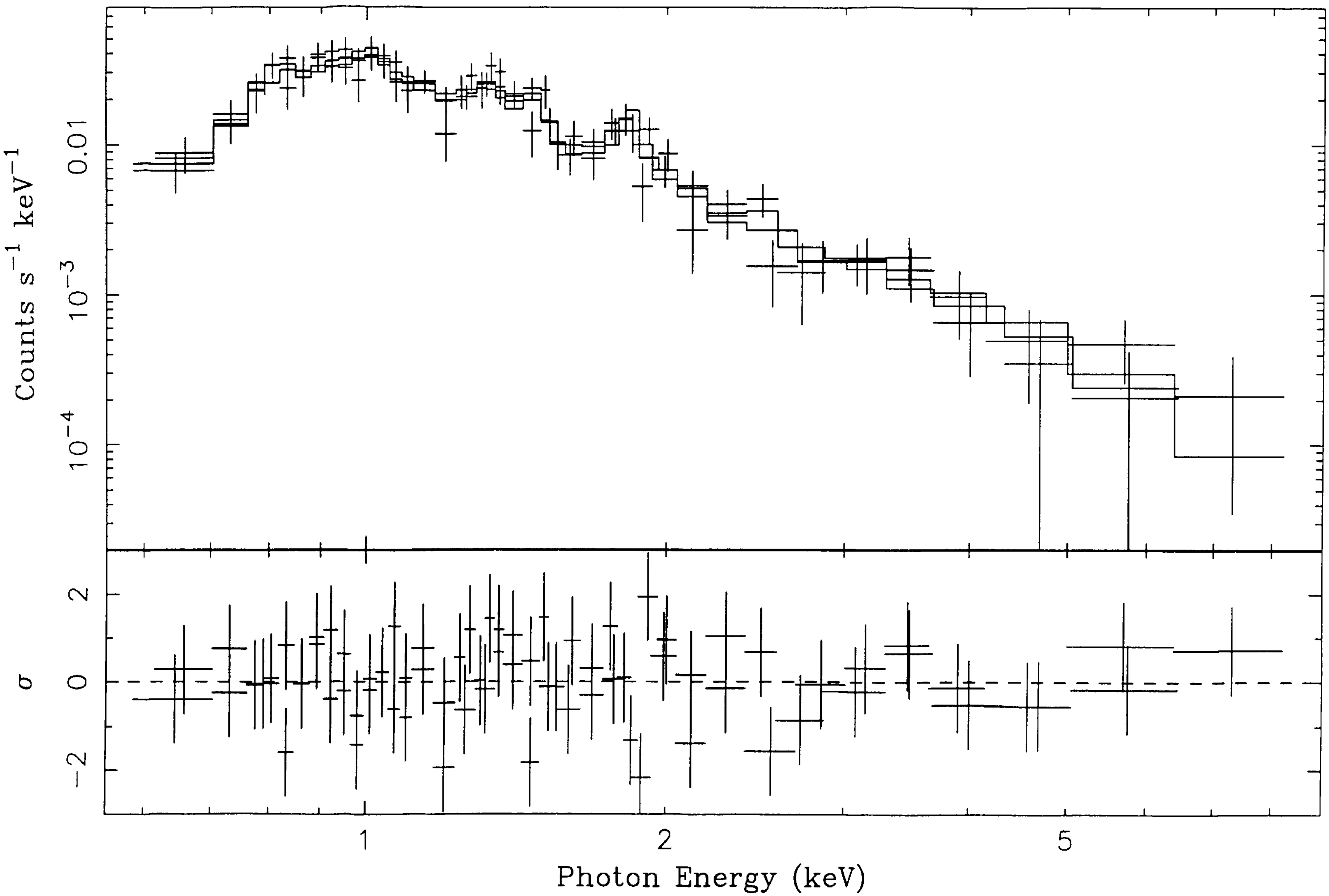
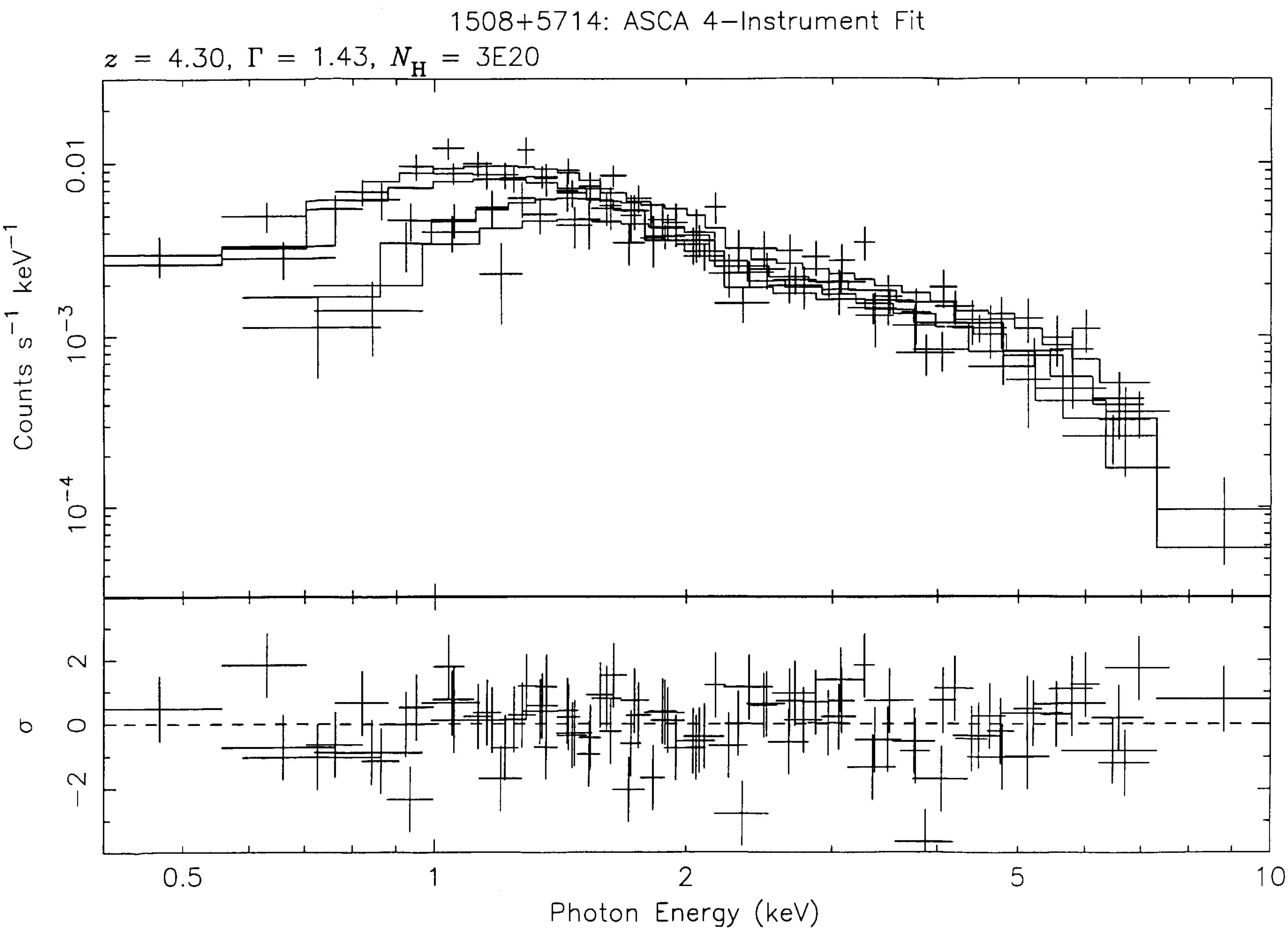


Figure 2: Power law fit to the data from all four instruments for the $z = 4.3$ quasar 1508+5714; a Galactic column density of $N_{\rm H} \sim 3 \times 10^{20}$ and an energy index of $\alpha = 0.43$ provide an adequate description for all the data.



1992; Williams et al. 1992). Hence, comparatively little is known about the characteristics of quasars above a few keV, where most of their X-ray energy is emitted.

X-ray spectroscopy of high-redshift quasars affords both rare access to the hard X-ray spectra of these objects and the opportunity to search for possible evolution of their high-energy properties. Recent *ROSAT* observations of $z \approx 3$ quasars in the 0.1–2.4 keV band have served both functions, providing spectra in the 0.5–10 keV rest frame energy range of objects emitting when the universe was roughly one-quarter its present age (Elvis et al. 1994; Bechtold et al. 1994a; Pickering, Impey, & Foltz 1994). Many of the same objects observed with *ROSAT* have been studied with the *ASCA* satellite in order to examine their spectral properties up to rest energies of $\sim$ 40 keV (Serlemitsos et al. 1994; Elvis et al. 1994; Siebert et al. 1996) . Some preliminary conclusions have been drawn about the X-ray spectral evolution of quasars (*e.g.*, Bechtold et al. 1994b), but to date just 25 objects with redshifts in excess of three have been detected in the X-ray band, and spectral information is available for only a fraction of these. Thus, each new high-z example provides a valuable datum for quasar evolution studies. It was for this reason that we obtained a deep *ASCA* pointing at the $z = 4.30$ quasar 1508+5714.

We discovered 1508+5714 and its X-ray emission as part of our followup of unidentified radio-selected X-ray sources in the *Einstein* Two-Sigma Catalog (Moran et al. 1996). Despite the fact that we found the quasar to be a relatively strong X-ray source (detected at the 6 σ level in a $\sim$ 2600 s exposure), it had apparently escaped notice in all previous analyses of the *Einstein* IPC image. Contemporaneous discovery of 1508+5714 was made by Hook et al. (1995) in their sample of flat-spectrum radio sources. Spurred by the Hook et al. report, Mathur & Elvis (1995) reanalyzed the *Einstein* image containing the quasar and also found that it was detected. 1508+5714 is presently the second most distant X-ray source known, just nosed out by the $z = 4.32$ object RX J1759.4+6638, which is more than 50 times fainter (Henry et al. 1994). The only other $z > 4$ quasar detected at X-ray wavelengths is 0000-263 ($z = 4.11$; Bechtold et al. 1994a), which is ten times fainter than 1508+5714. Thus, 1508+5714 currently provides the only opportunity to study in detail quasar X-ray emission above a redshift of 4. We have measured its spectrum in the 0.5–10 keV *ASCA* bandpass, which corresponds to the 3–53 keV band in the rest frame of the quasar.

1508+5714 was observed with the *ASCA* satellite on two occasions, first on 1995 March 2 and then again on 1995 December 15. Data collected with both sets of instruments on board *ASCA*, the Gas Imaging Spectrometers (GIS2 and GIS3) and the Solid-state Imaging Spectrometers (SIS0 and SIS1), were filtered following the guidelines described in The ABC Guide to *ASCA* Data Reduction (Day et al. 1995). A total of 92.0 ksec of good exposure was obtained with each of the GIS detectors: 53.3 ksec during the first observation and 38.7 ksec during the second. Exposure times with the SIS instruments, which were operated in 1-CCD mode, totaled 83.6 and 82.9 ksec for SIS0 and SIS1, respectively. Fifty-eight percent of the SIS exposure was obtained during the 1995 March observation.

Source counts were extracted from a region $6'$ in radius centered on the quasar in the GIS images and from a region $3'$ radius in the SIS images. To measure the background contribution, we collected counts at the same off-axis angle in other parts of the detector. The resulting spectrum is shown in Figure 2. It is remarkably consistent with a single power law of index ~ 0.4 throughout the entire 3-53 keV (rest frame) band. Strong upper limits to emission and absorption features have been obtained.

A draft of a paper describing this, the only high quality X-ray spectrum of a $z > 4$ quasar yet obtained, is in final preparation, and will be submitted to the *Astrophysical Journal (Letters)* shortly.

IV. Pulsar Polar Caps: The Smallest X-ray Sources in the Universe

The one observation granted under this proposal was for the 3 million-year-old nearby radio pulsar PSR1929+10. Our analysis of the ROSAT PSPC data on this source indicated that we were seeing thermal emission from the pulsar polar cap, a region only ~ 40 m in radius; from the observed spectrum and pulse shape, we set limits on the radius of the neutron star using the predicted gravitational light bending near the surface from General Relativity. Our goal was to obtain a higher signal to noise light curve and to see how well the blackbody spectral fit from *ROSAT* extrapolated to the *ASCA* band.

It doesn't. The 80 ksec *ASCA* pointing yielded a hard power law component extending up to > 6 keV. In addition, the *ASCA* image appears to show a hard region of diffuse emission extending $> 10'$ from the pulsar (Kawai 1996) which has a similar spectrum. Neither a simple power law or a thermal spectrum can adequately fit the whole *ASCA* spectrum, let alone include the PSPC data simultaneously.

Using some recently acquired *ROSAT* HRI observations along with these data, we are now attempting to come up with a self-consistent model for the spectrum and pulse shape of PSR 1929+10. We anticipate the completion of this analysis by the end of the calendar year, and the submission of a paper describing our results by the end of the current grant year.

V. Eye in the Sky: A New Look at the Starburst/Seyfert Connection

The observation of *IRAS* $00317-2152$ proposed under this program has been completed, but there is a problem in the first-level data processing which has prevented us from analyzing it. We expect this to be cleared up soon so that we can proceed to explore the X-ray properties of this source which is typical of several far IR and X-ray luminous objects we have discovered which display optical spectra dominated by starburst features along with weak indications of Seyfert activity.

VI. CoInvestigator programs

The PI of this grant has completed two other papers during the current year on *ASCA* projects for which he was a co-Investigator. Hughes et al. (ApJL, 444, L81) describes how, for the first time, ASCA allows the spectral classification of supernova remnants into Type Ia and Type II, corresponding to the two primary mechanisms of supernovae – thermonuclear explosion and core collapse. It presents high-quality spectra of three SNRs in the Large Magellanic Cloud, concluding that all three are of Type Ia.

In Harrus, Hughes, and Helfand (1996 ApJL, 464, L161), we demonstrate the discovery of a diffuse, nonthermal X-ray nebula in the vicinity of the pulsar associated with the middle-aged supernova remnant W44. The source is spatially coincident with a recently discovered flat-spectrum radio nebula, confirming it as a new addition to the small class of pulsar-powered nebulae within SNR shells. We show that the source is consistent with previously suggested correlations between the pulsar spin-down power and the nebular luminosity.